



CLARREO IR Instrument Prototype Progress:

Vacuum Testing of the
UW Absolute Radiance Interferometer (ARI)
with end-to-end Verification Tests to bring the instrument to TRL 6

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Jon Gero, Doug Adler, Don Thielman, Jeff Wong,
Nick Ciganovich, Claire Pettersen, John Perepezko,
Dave Hoese, Ray Garcia, Bob Knuteson, Dave Tobin



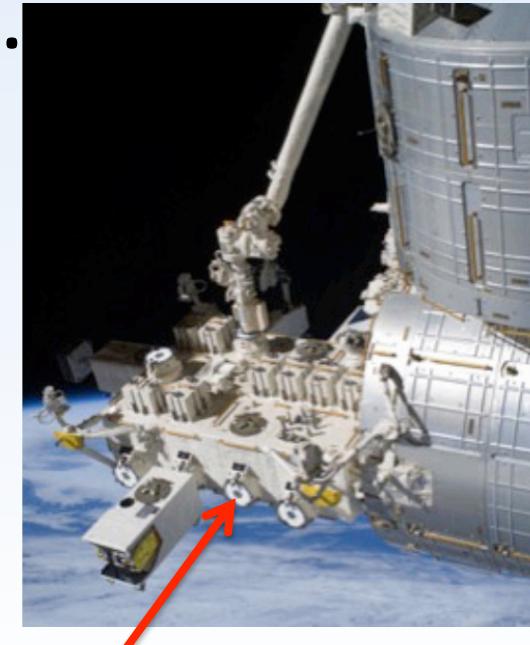
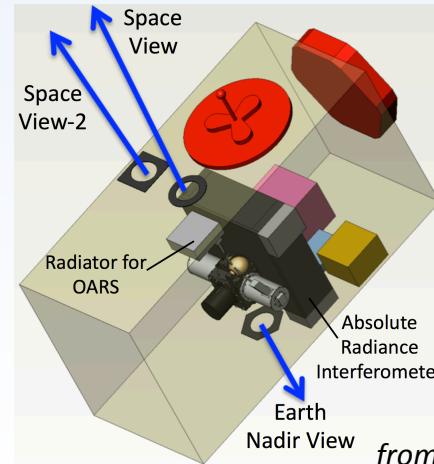
**University of Wisconsin-Madison
Space Science and Engineering Center**

**CLARREO Science Definition Team Meeting
NASA GSFC, 7-9 January 2014**



Executive Summary

- Vacuum Testing of CLARREO Flight Prototype *Absolute Radiance Interferometer (ARI)* has demonstrated 0.1 K 3-sigma performance of the (1) Calibrated FTS (CFTS) and (2) On-orbit Verification and Test System (OVTS), bringing the full ARI system to TRL 6.
- The next step should leverage NASA ESTO's investment with a spaceborne demonstration as a CLARREO IR pathfinder. The right opportunity needs to be found, possibly on the ISS.



JEM-EF EFU Site #4
from ISS/DS/ESM Cross Mission Study

CLARREO is Ready to Go



Close-Out Review

Vacuum Testing of the UW Absolute Radiance Interferometer (ARI) With End-to-End Verification Tests to Bring the Instrument to TRL 6

Contract Number NNL10AA12B, Task Order-2, Number NNL12AQ08T, Item Number 001

Hank Revercomb, PI

University of Wisconsin

Space Science and Engineering Center



25 September 2013

Version 4.5



ESTO Conclusion: This IR demonstration along with the UV/SOLAR work represents closing the gap between what was possible when the CLARREO Mission stood up and the fact that **it is actually achievable and demonstrated now**

NASA Instrument Incubator Program

A New Class of Advanced Accuracy Satellite Instrumentation (AASI)
for the CLARREO Mission

NASA IIP-07-0006

Final Report

University of Wisconsin-Madison
Space Science and Engineering Center

Henry Revercomb, PI
Fred Best, Co-I
John Perepezko, Co-I (UW Materials Science)

and

Harvard University
John Dykema, Co-I

November 2013



FINAL REPORT

Contract Number: NNL10AA12B
Task Order-2 Contract Number: NNL12AQ08T
Item Number: 001

UW-SSEC IPT Task:
Vacuum Testing of the UW Absolute Radiance Interferometer (ARI) With End-to-End Verification Tests to Bring the Instrument to TRL 6

University of Wisconsin
Space Science and Engineering Center

November 2013



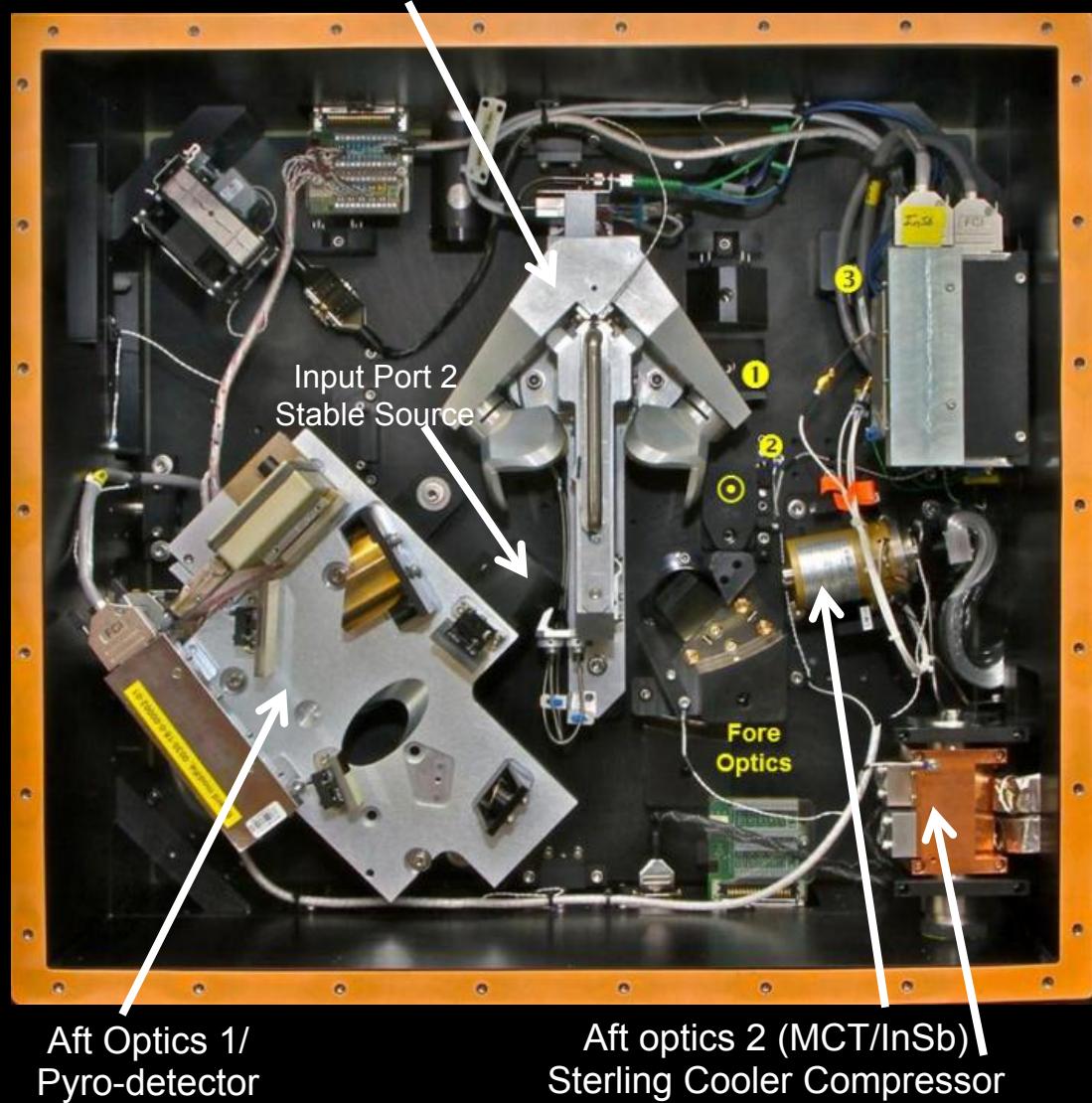
Data and information contained in the pages of this Final Report furnished in conjunction with the contract referenced above, shall not be used or disclosed, except for evaluation purposes.

Topics: IR Measurement Science

- ARI Flight Prototype for CLARREO:
Summary of instrument developed under
NASA ESTO support of UW/Harvard IIP &
follow-on vacuum testing
- ARI Vacuum Test Results:
demonstrate 0.1 K 3-sigma performance of
Calibrated FTS (CFTS) and
On-orbit Verification and Test System (OVTS)

Absolute Radiance Interferometer (ARI) Prototype with a short upgrade path to flight

ABB Bomem Interferometer
Modulator "Wishbone"



Calibrated FTS

- Corner-cube interferometer used in 4-port to avoid double pass; Strong flight heritage
 - 0.5 cm^{-1} resolution ($\pm 1 \text{ cm OPD}$)
 - $1.55 \mu\text{m}$ diode laser for interferogram sample control & fringe counting
 - 10 cm CsI single-substrate beamsplitter
- Fore optics designed to
 - minimize polarization effects
 - minimize sizes of calibration/validation BBs & reflectivity sources
 - minimize stray light by providing effective field and aperture stops
 - maximize energy throughput
- 3-50 μm Spectral Coverage
 - Highly linear pyroelectric detector, all reflective aft optics: 10-50 μm
 - Cryo-cooler for MCT & InSb semiconductor detectors: 3-18 μm

Absolute Radiance Interferometer (ARI) Prototype

with a short upgrade path to flight

On-orbit Verification and Test System (OVTS) Technologies

① On-orbit Absolute Radiance

Standard (OARS) cavity blackbody using three miniature phase change cells to establish the temperature scale from -40, to +30 C to better than 10 mK

② On-orbit Cavity Emissivity

Module (OCEM) using Heated Halo source allowing the FTS to measure the broadband spectral emissivity of the OARS to better than 0.001

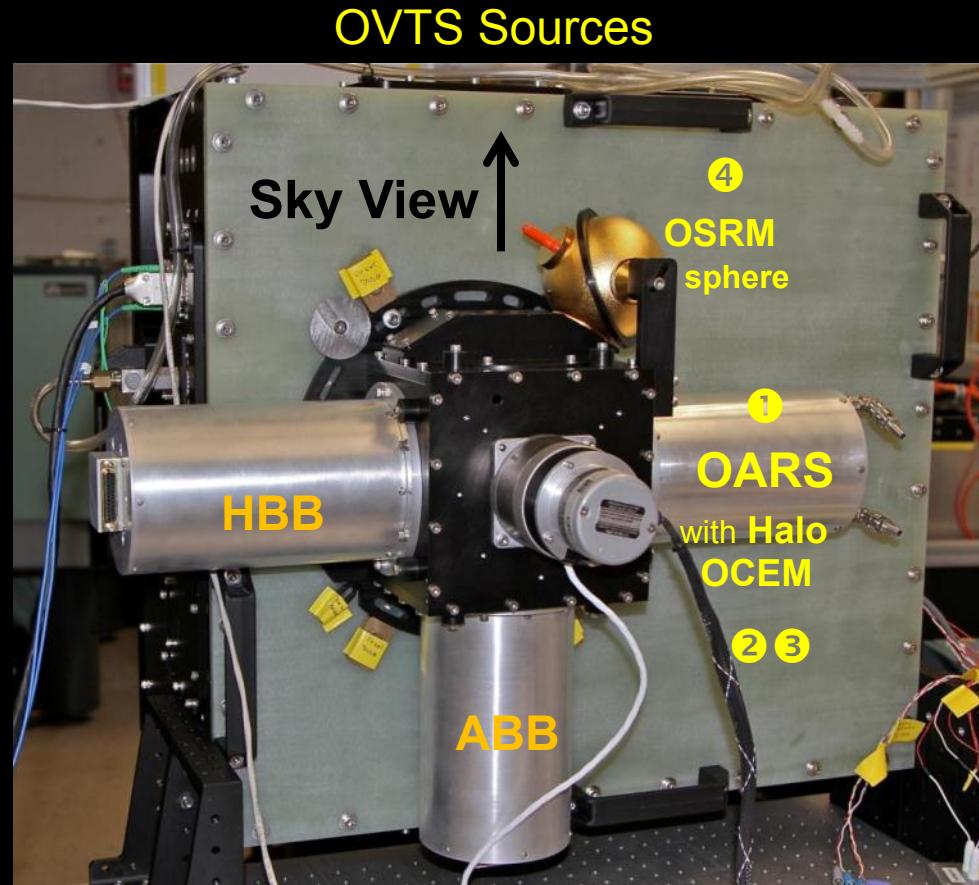
③ OCEM-QCL* using a Quantum

Cascade Laser source to monitor changes in the mono-chromatic cavity emissivity of the OARS & Cal BB to better than 0.001

④ On-orbit Spectral Response

Module* (OSRM) QCL used to measure the FTS instrument line shape

* QCL functions demonstrated separately

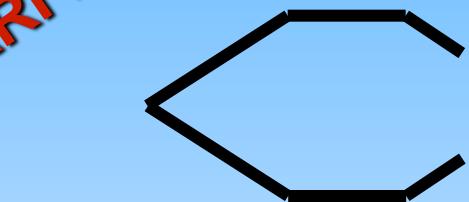


Calibrated FTS Blackbodies (HBB & ABB)

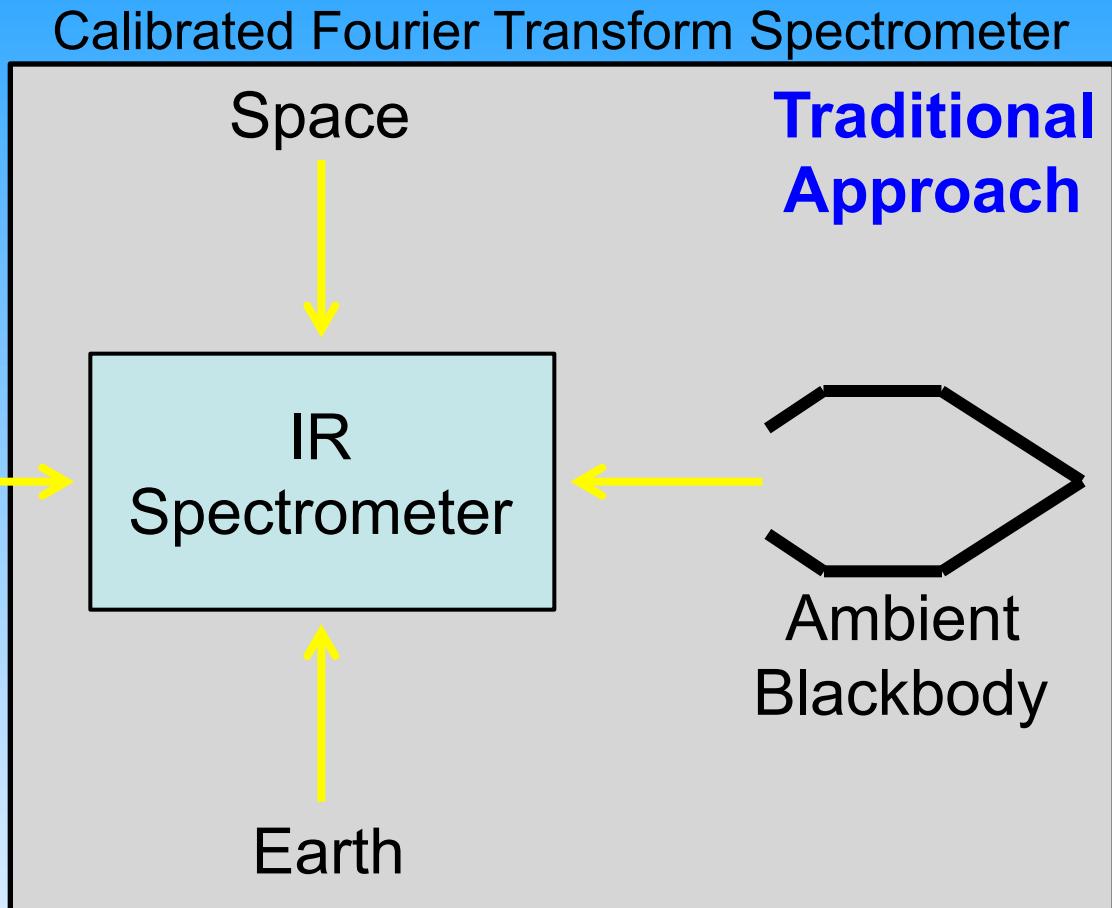
All components at flight scale

On-Orbit Verification and Test System

A key
new System
that really sets the
ARI for CLARREO apart



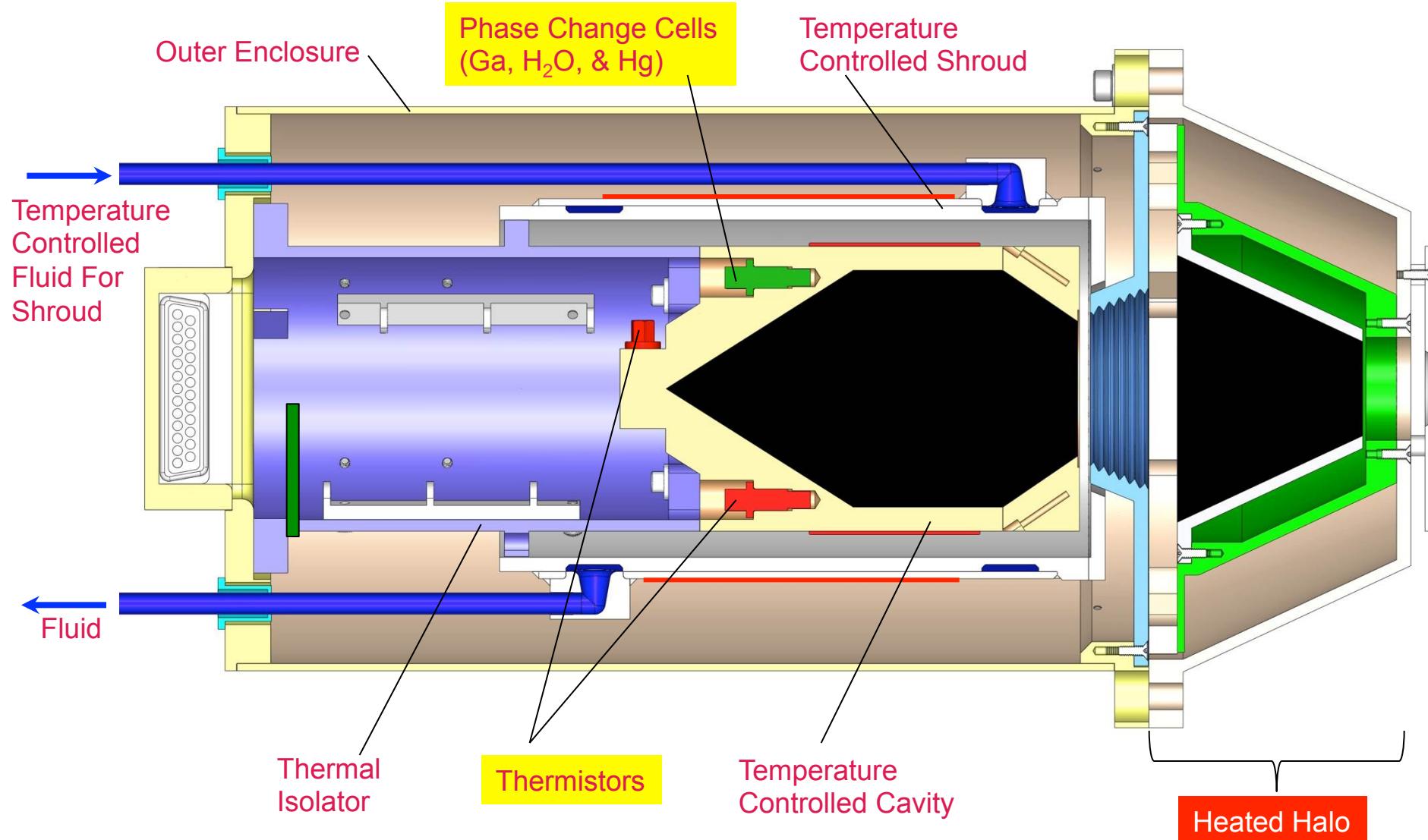
**On-Orbit Absolute
Radiance Standard
(OARS, with wide
Temperature range)**



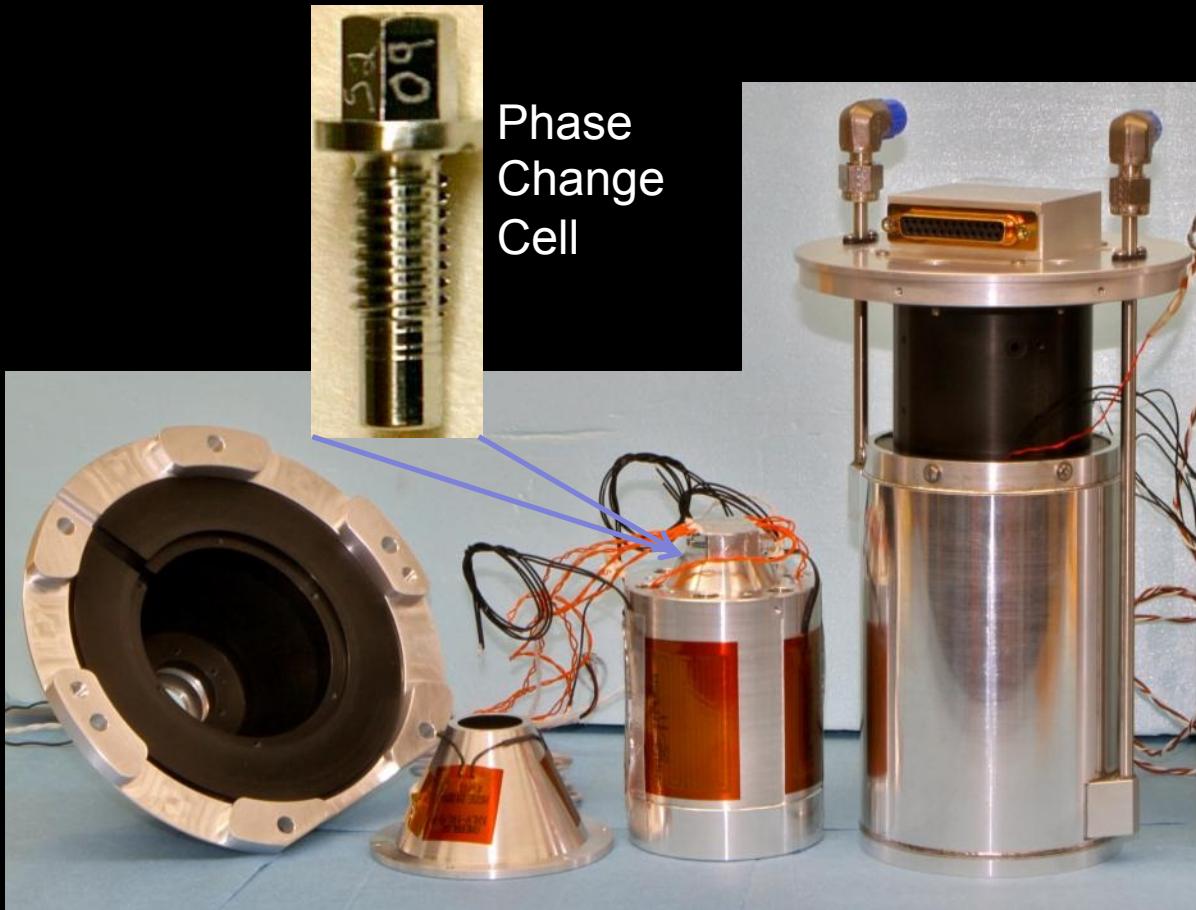
OVTS Provides On-Orbit, End-to-End Calibration
Verification & Testing Traceable to Recognized SI Standards

OARS Design with GIFTs Spaceflight Design Heritage

(laboratory version)



On-orbit Absolute Radiance Standard OARS

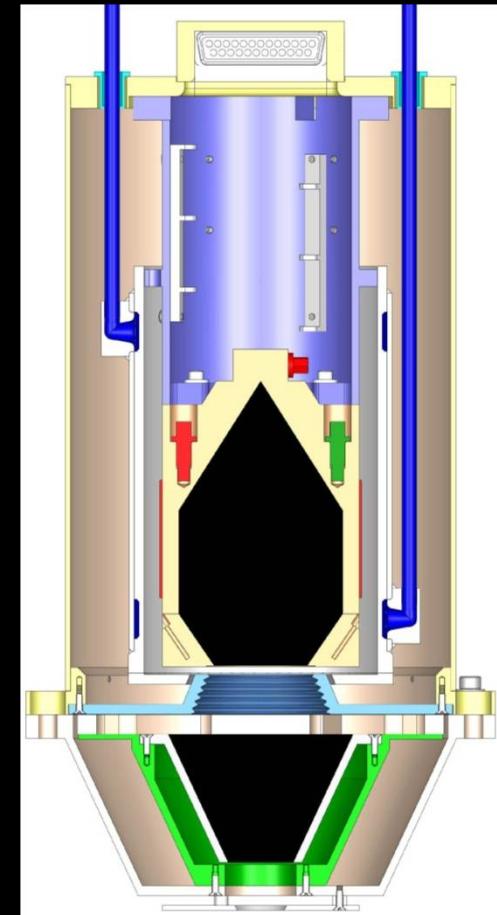


Heated Halo
& Halo Insulator

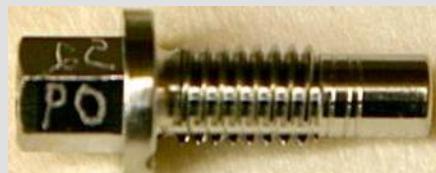
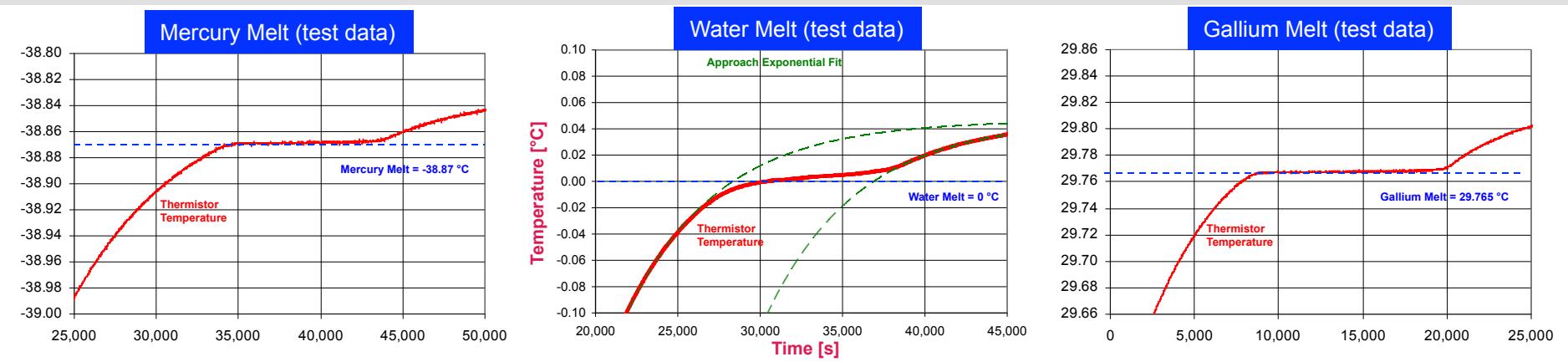
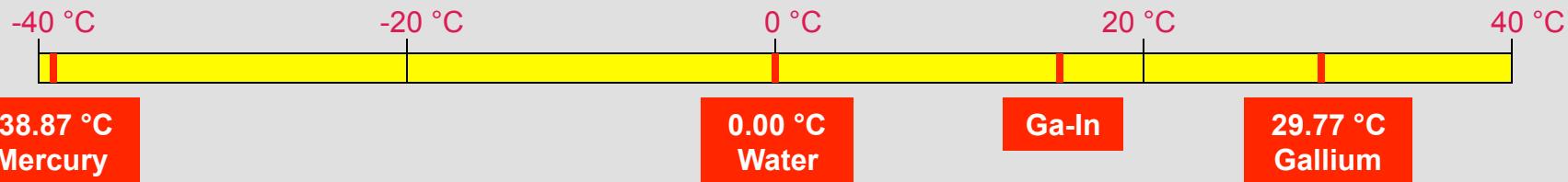
Cavity

Inner Shield
& Isolator

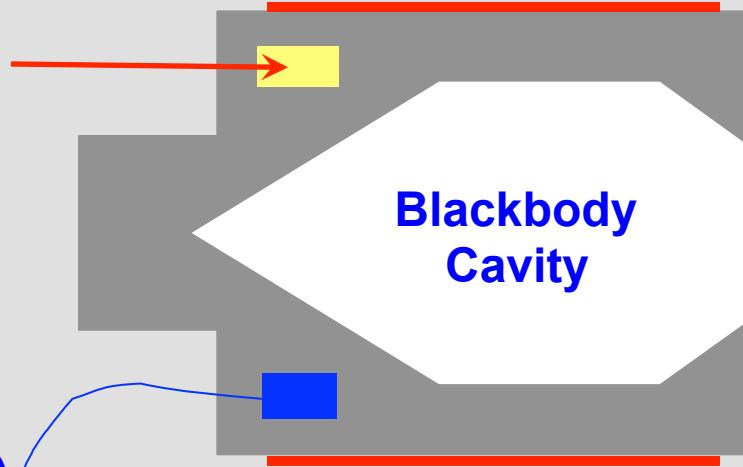
Assembly Diagram



Melt Signatures Provide Temperature Calibration

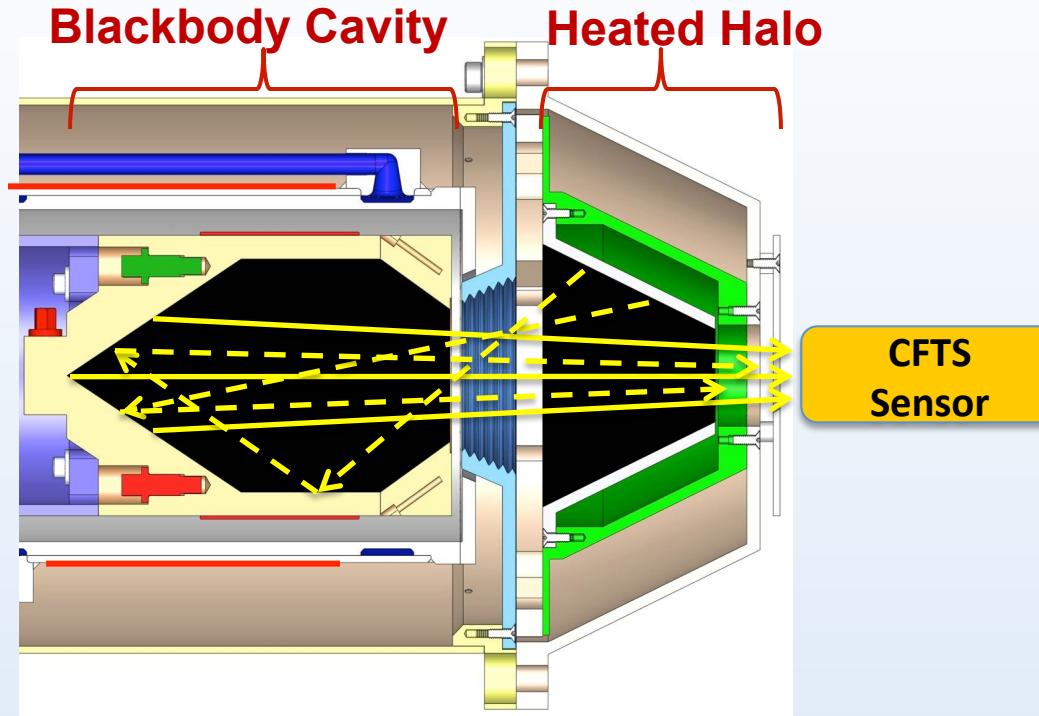


Phase Change Cell
(Ga, H₂O, or Hg)



Plateaus (shown in plots)
provide known
temperatures to
better than 10 mK

Heated Halo Concept



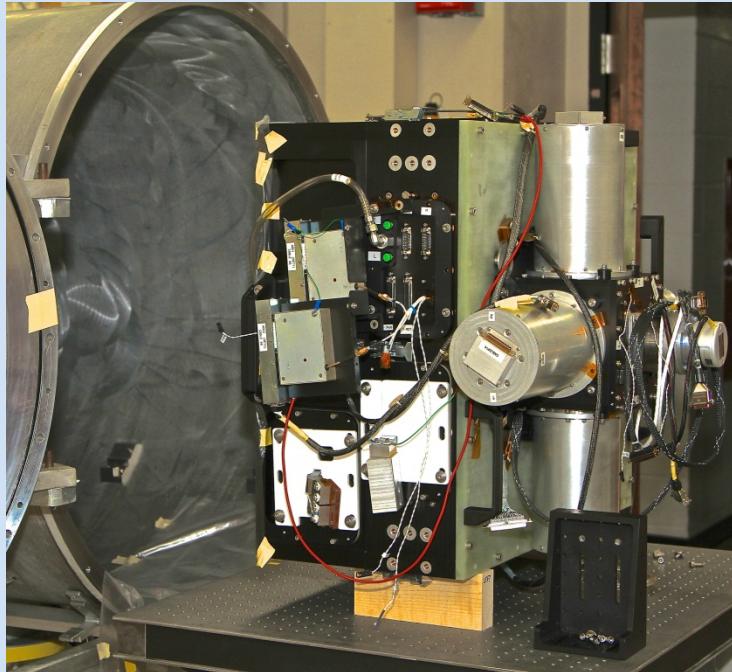
$$R_{\text{scene}} = \varepsilon \bullet B(T_{\text{BB}}) + (1 - \varepsilon) \bullet [F \bullet B(T_{\text{Halo}}) + (1 - F) \bullet B(T_{\text{room}})]$$

Radiance emitted from BB

Background Radiance Reflected from BB

$$\langle 1 - \varepsilon_{\tilde{\nu}}(t) \rangle_t = \left\langle \frac{R_{\text{scene}}(t) - B[T_{\text{BB}}(t)]}{R_{\text{background}}(t) - B[T_{\text{BB}}(t)]} \right\rangle_t$$

Vacuum Testing Configuration



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demonstrate 0.1 K 3-sigma performance of
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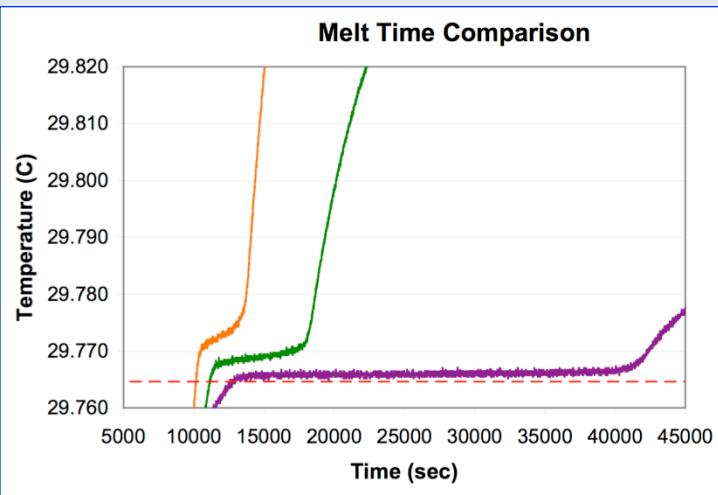
ARI Tests Conducted Under Vacuum

- ✓ Detector performance testing and characterization.
- ✓ Signal chain nonlinearity characterization and analysis.
- ✓ Instrument spectral radiometric uncertainty analysis.
- ✓ OARS thermal gradient and temperature measurement uncertainty analysis.
- ✓ OCEM Heated Halo verification blackbody emissivity measurement demonstration.
- ✓ Radiometric verification using OARS (-50 °C to +60 °C).
- ✓ Instrument spectral radiometric uncertainty demonstration in presence of expected on-orbit thermal perturbations.

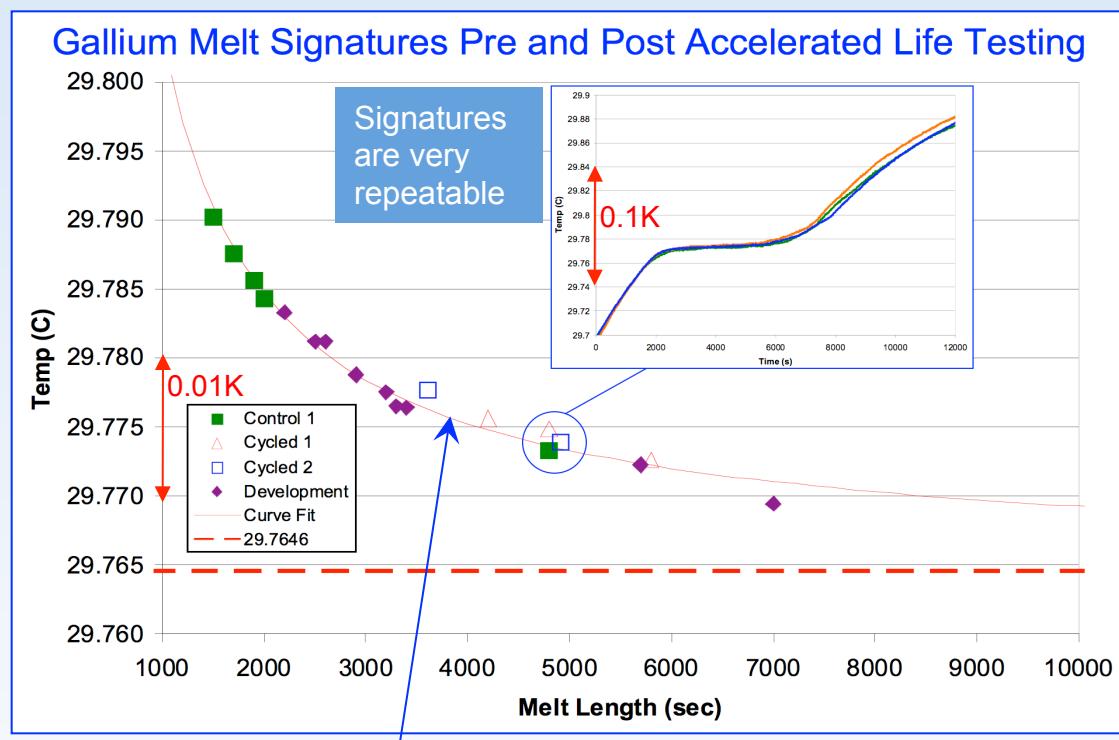
Vacuum Test Results

- OARS Phase Change Cells
- OARS thermal gradient and temperature measurement uncertainty analysis

Signature Dependence on Melt Length the Characteristic Curve

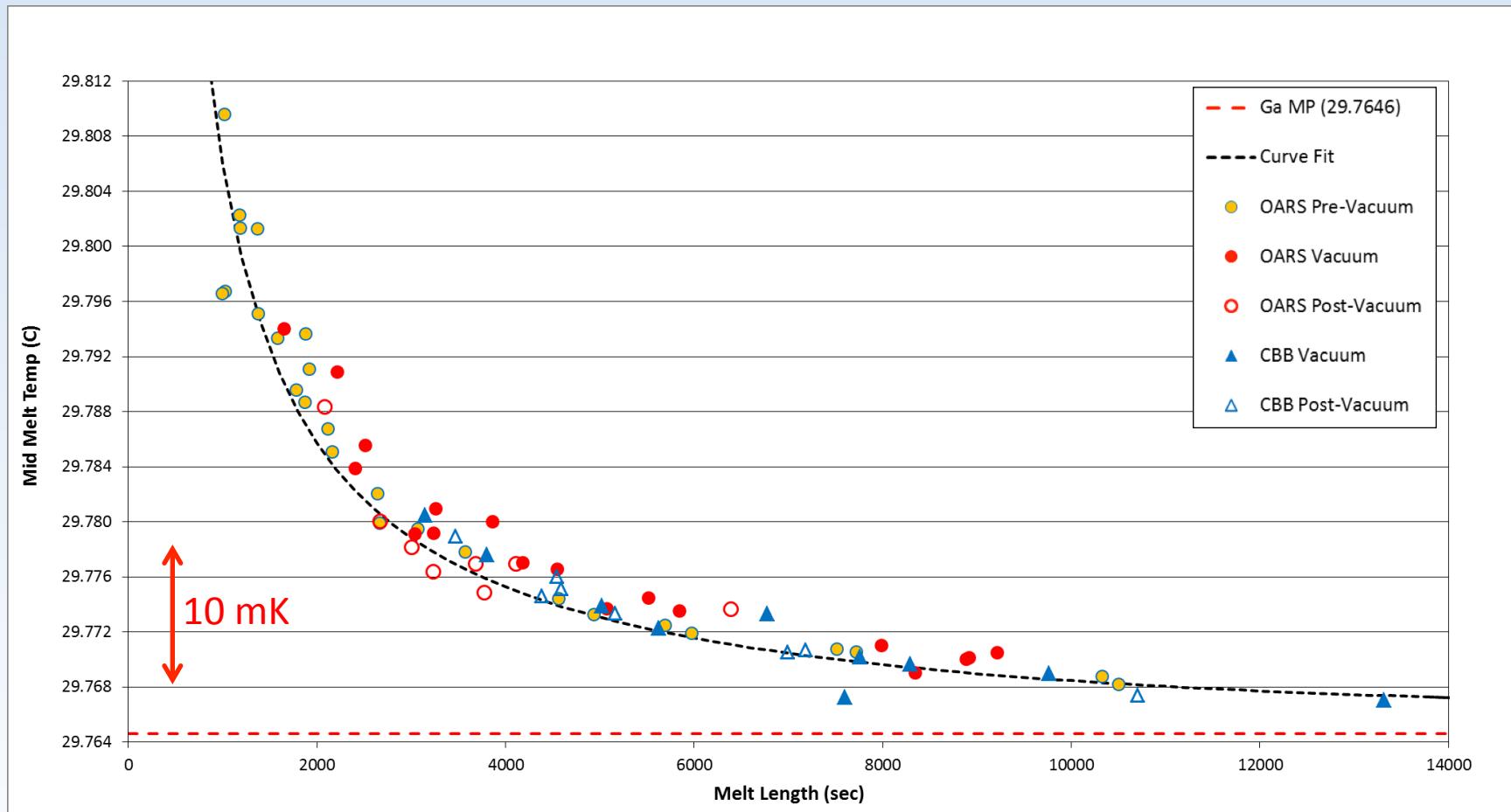


Melt curves that are flatter and approach the theoretical melt temperature are obtained with longer melt times.



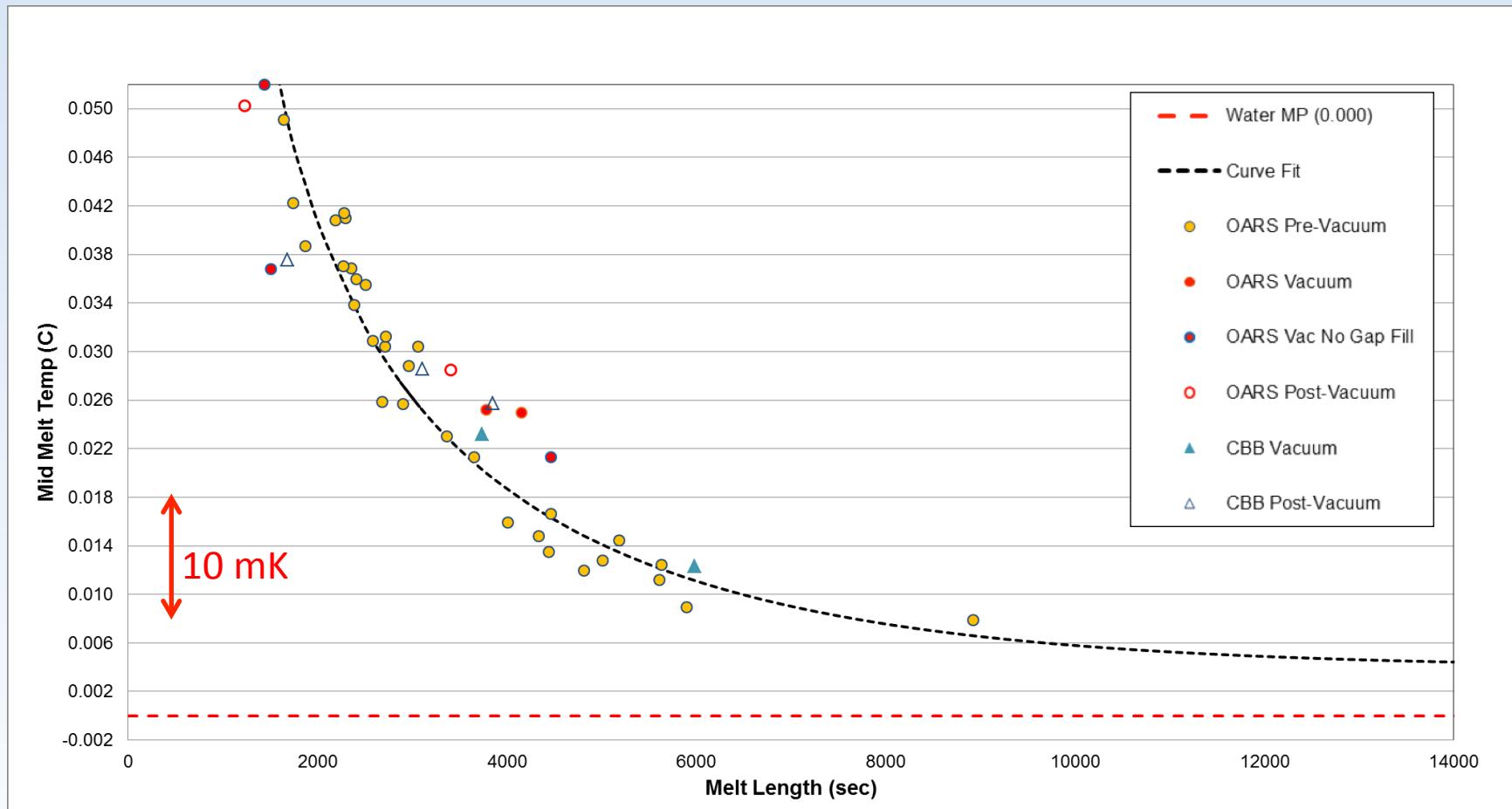
The **Characteristic Curve** defines the mid-melt temperature vs melt length relationship. This relationship has been shown to be very stable for a given physical configuration and it can be very well characterized.

Gallium Melts - Vacuum



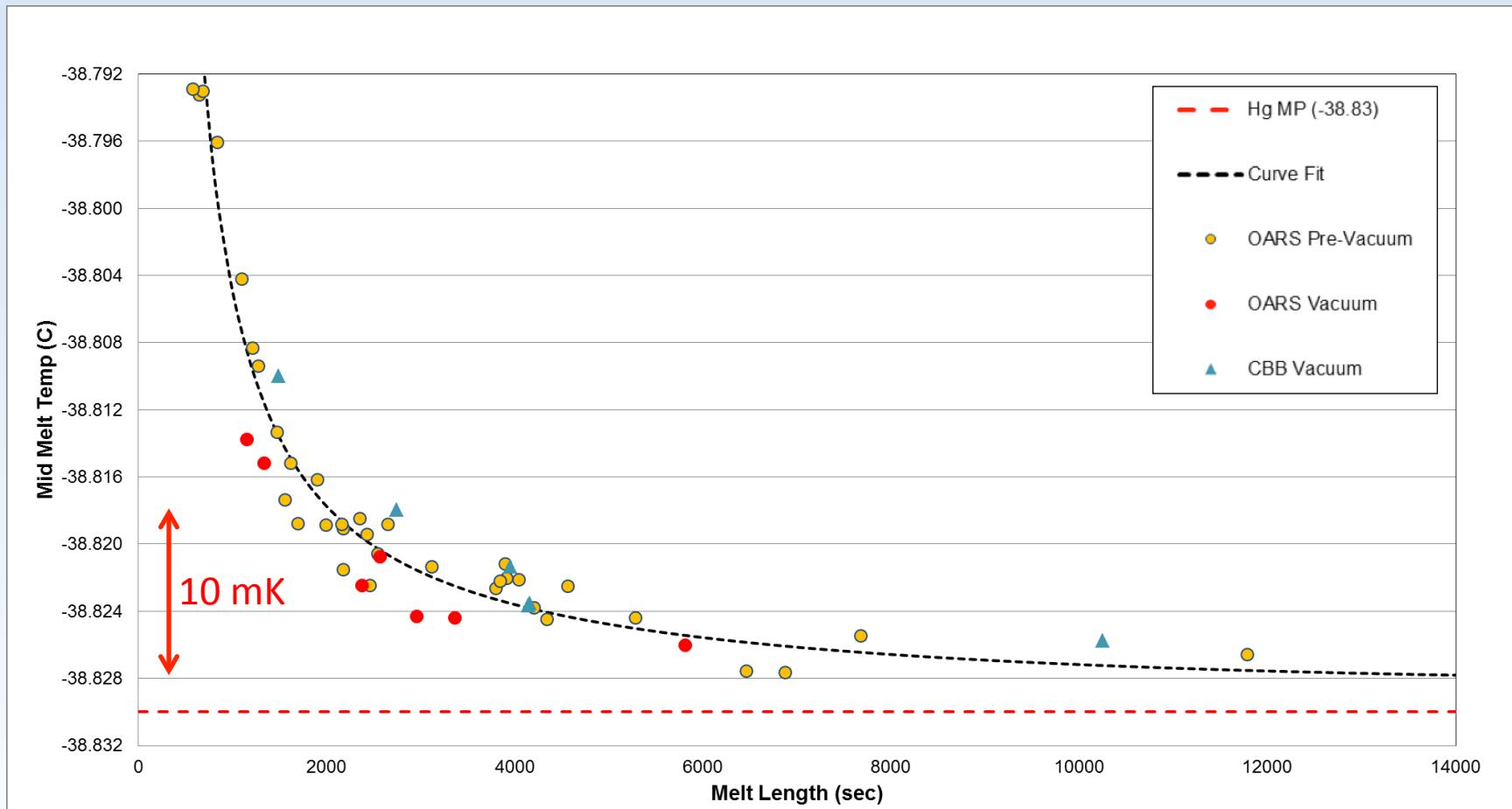
**Melt behavior in a vacuum environment is very close
to what was demonstrated in 1 atmosphere**

Water Melts - Vacuum



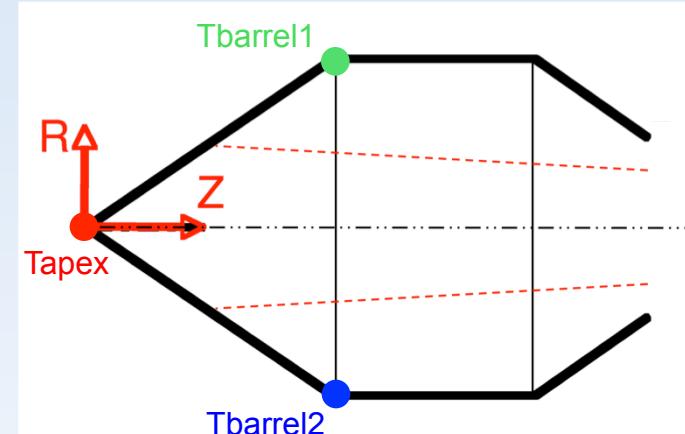
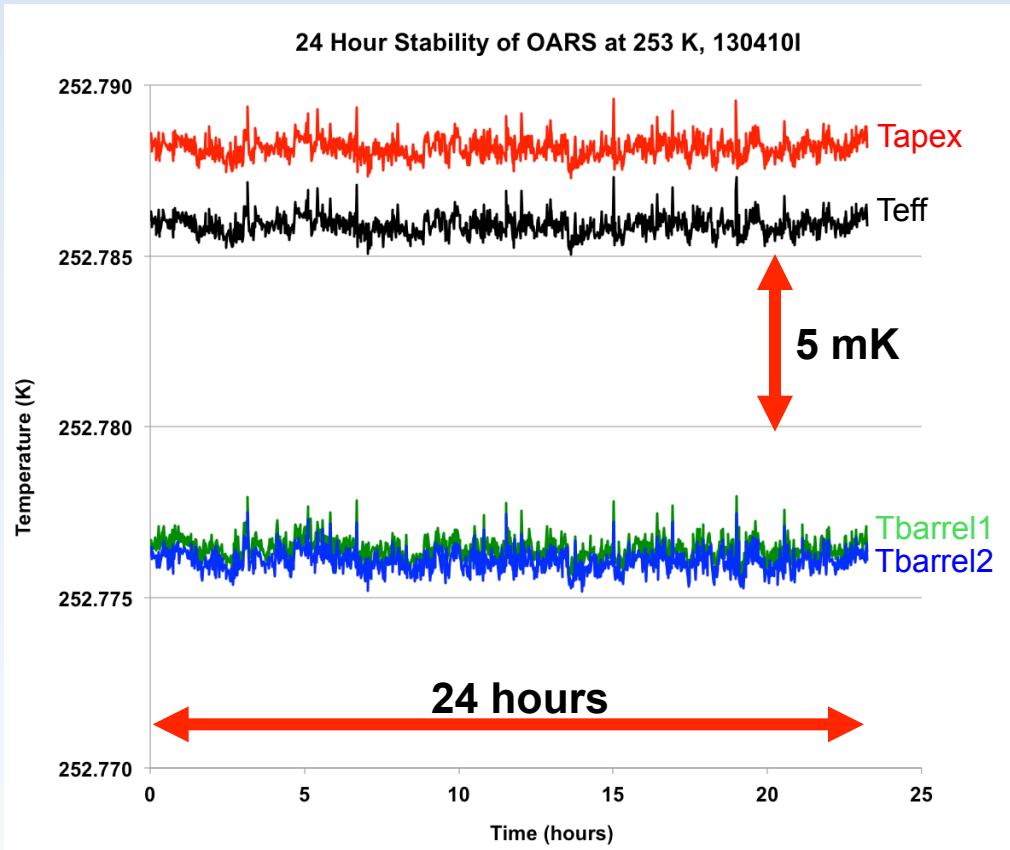
**Melt behavior in a vacuum environment is very close
to what was demonstrated in 1 atmosphere**

Mercury Melts - Vacuum



Melt behavior in a vacuum environment is very close
to what was demonstrated in 1 atmosphere

OARS 24 Hour Stability at -20 C under Vacuum



The maximum gradient of 15 mK shown here at -20 C, would be expected to double to 30 mK at an OARS temperature of -60 C.

$$\text{Teff} = 0.811 * \text{Tapex} + 0.095 * \text{Tbarrel1} + 0.095 * \text{Tbarrel2}$$

The thermistor weighting takes into account the linear temperature gradient from the cavity barrel to the apex, and the geometry of the field of view. The temperature at the cavity aperture is 0.1K lower than Teff.

OARS Blackbody Temperature Uncertainty Budget (3 sigma)

Temperature Uncertainty (3 sigma)	Laboratory OARS & ARI Cal Sources	On-Orbit ARI Cal Source	On-Orbit OARS	Comments for On-Orbit OARS
Temperature Calibration Standard				
(Thermometrics SP60 Probe with Hart Scientific 2560 Thermistor Module)	0.005	0.005	0.010	Phase Change Calibration Uncertainty
Blackbody Readout Electronics Uncertainty				
Readout Electronics Uncertainty (at delivery)	0.001	0.005	0.000	Combined with above for On-orbit
Blackbody Thermistor Temperature Transfer Uncertainty				
Gradient Between Temperature Standard and Cavity Thermistors	0.010	0.010	0.008	
Calibration Fitting Equation Residual Error	0.002	0.002	0.015	
Cavity Temperature Uniformity Uncertainty				
Cavity to Thermistor Gradient Uncertainty (1/2 of total max expected gradient)	0.015	0.015	0.015	
Thermistor Wire Heat Leak Temperature Bias Uncertainty*	0.020	0.008	0.020	
Paint Gradient (due to radiative coupling to surrounding temperatures)	0.018	0.015	0.018	
*(due to conductive coupling of leads to a temperature different than the cavity)				
Long-term Stability				
Blackbody Thermistor (value for 8 years of drift assuming 100 C is 5mK)	0.005	0.010	0.005	Short Term Stability
Blackbody Controller Readout Electronics	0.000	0.015	0.005	Short Term Stability
Effective Radiometric Temperature Weighting Factor Uncertainty				
Monte Carlo Ray Trace Model Uncertainty in Determining Teff (radiometric error that accounts for non-isothermal cavity temperature)	0.030	0.025	0.025	Improved with better modeling
RSS combination of all contributors:				
	0.045	0.040	0.045*	

*Value used in ARI Radiometric Uncertainty Analysis

Vacuum Test Results

Heated Halo Emissivity Measurement

Traceable Blackbody Radiance

Planck Function:

$$B_{\tilde{\nu}}(T) = \frac{2hc^2\tilde{\nu}^3}{\exp(h\tilde{\nu}c/k_B T) - 1}$$

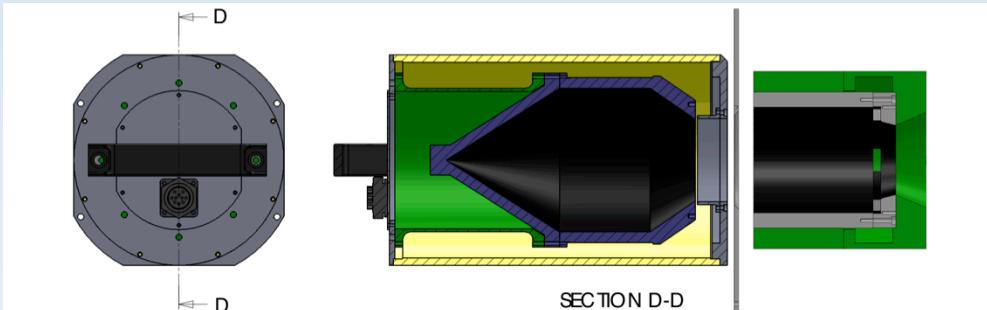
Model of Blackbody Radiance:

$$R_{\tilde{\nu}}(\epsilon_{\tilde{\nu}}, T) = \epsilon_{\tilde{\nu}} \cdot B_{\tilde{\nu}}(T_{\text{blackbody}}^{\text{eff}}) + (1 - \epsilon_{\tilde{\nu}}) \cdot B_{\tilde{\nu}}(T_{\text{background}}^{\text{eff}})$$

Both temperature and emissivity of a blackbody must be known — on-orbit — throughout the lifetime of the instrument

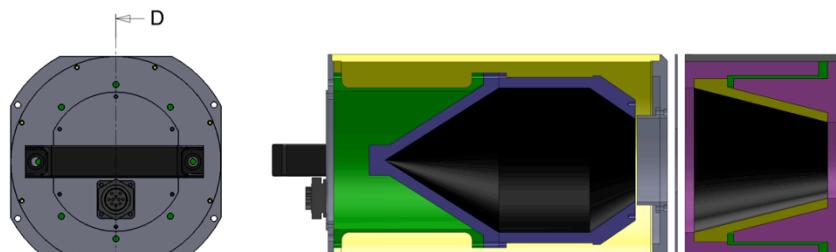
Heated Halo Development under IIP

Gen. 1



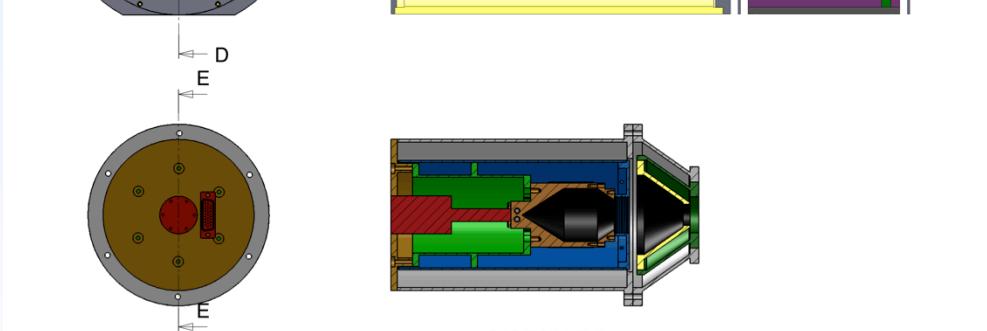
TRL 4

Gen. 2



TRL 5

Gen. 3

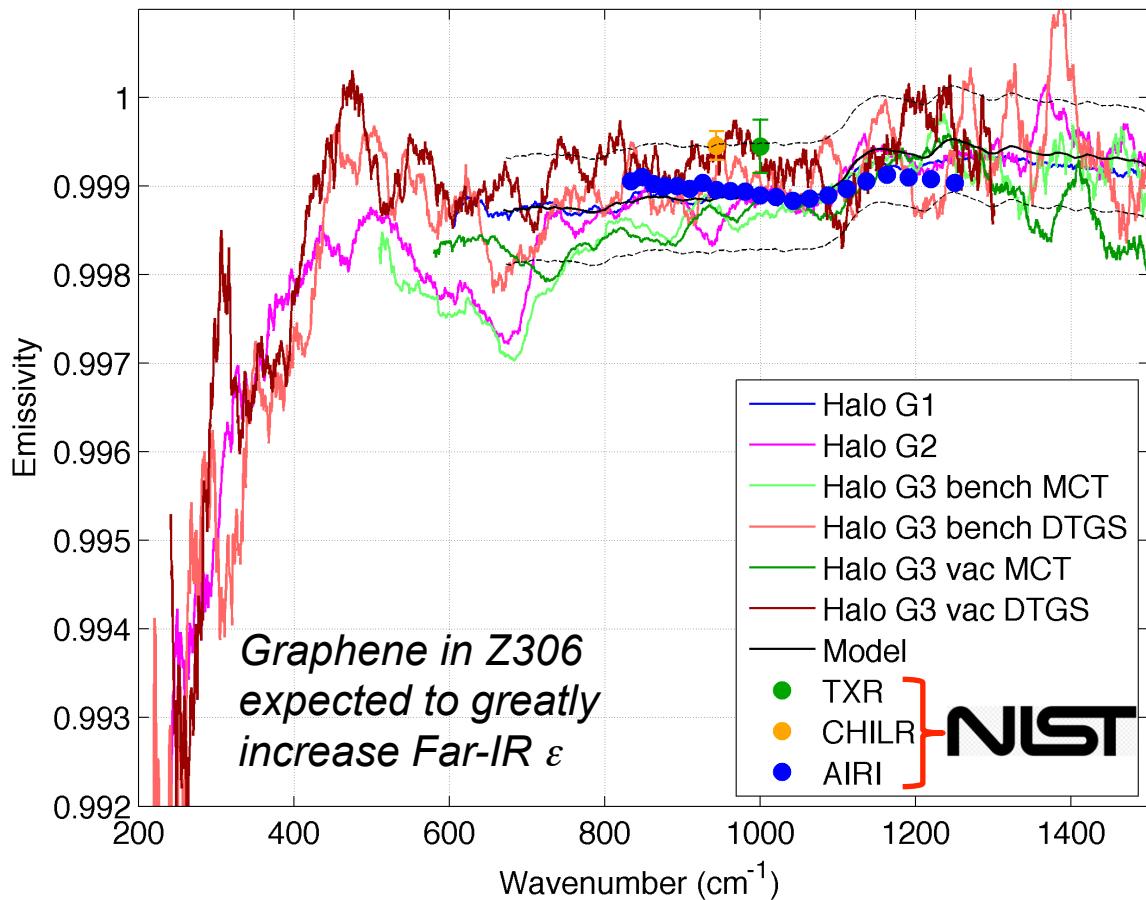


TRL 6



Flight Cavity (3.0 cm aperture diameter) and halo design

Blackbody Emissivity Comparison



3- σ emissivity of 0.0006 uncertainty indicated by dashed lines applied to model

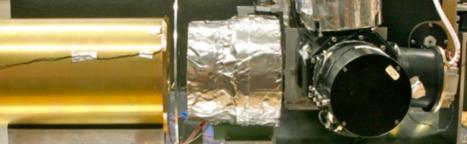
Good agreement with NIST measurements

Continued work corroborates earlier results and helps reduce uncertainty

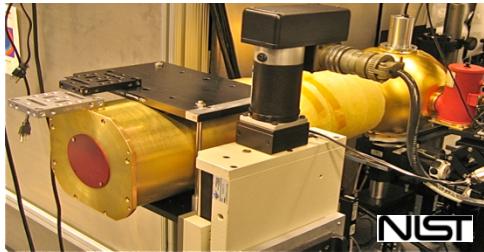
UW Heated Halo



CLARREO IIP



NIST CHILR



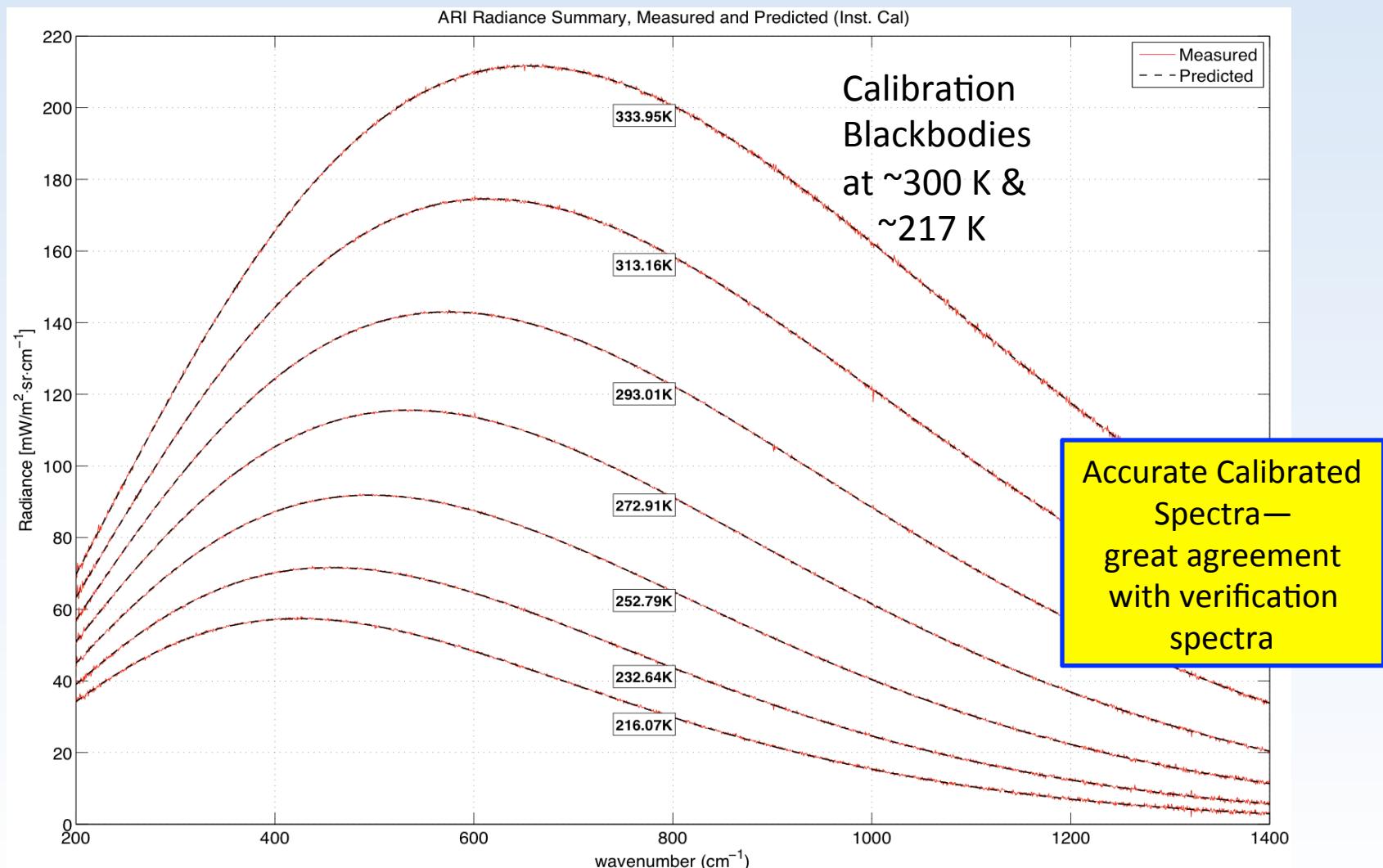
NIST AIRI



Vacuum Test Results

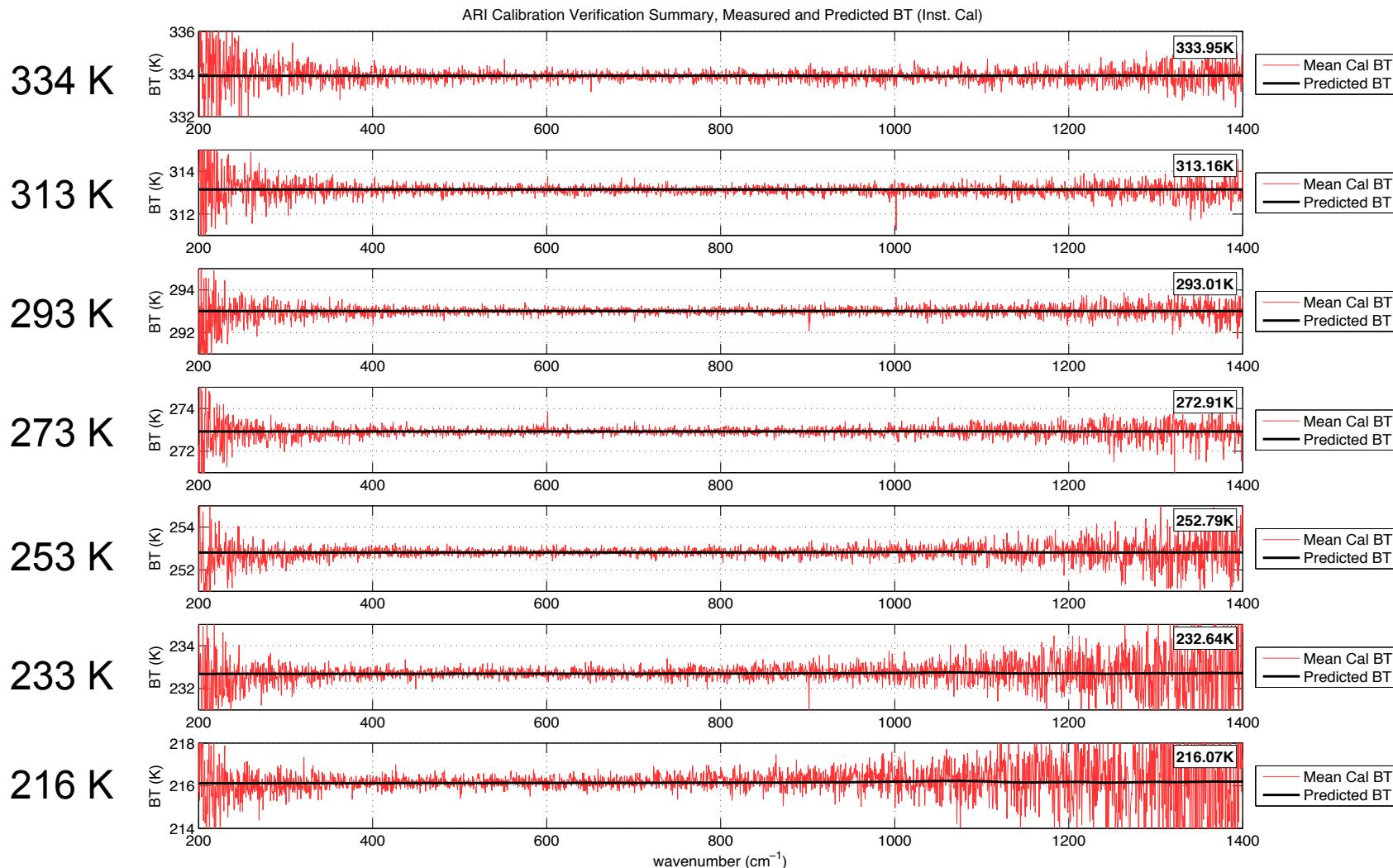
Radiometric Verification Using OARS

Mean Calibrated Radiance Spectra (DTGS) Compared to OARS Radiance Spectra



Brightness Temperature Comparison (DTGS)

(CFTS calibrated and OARS verification)



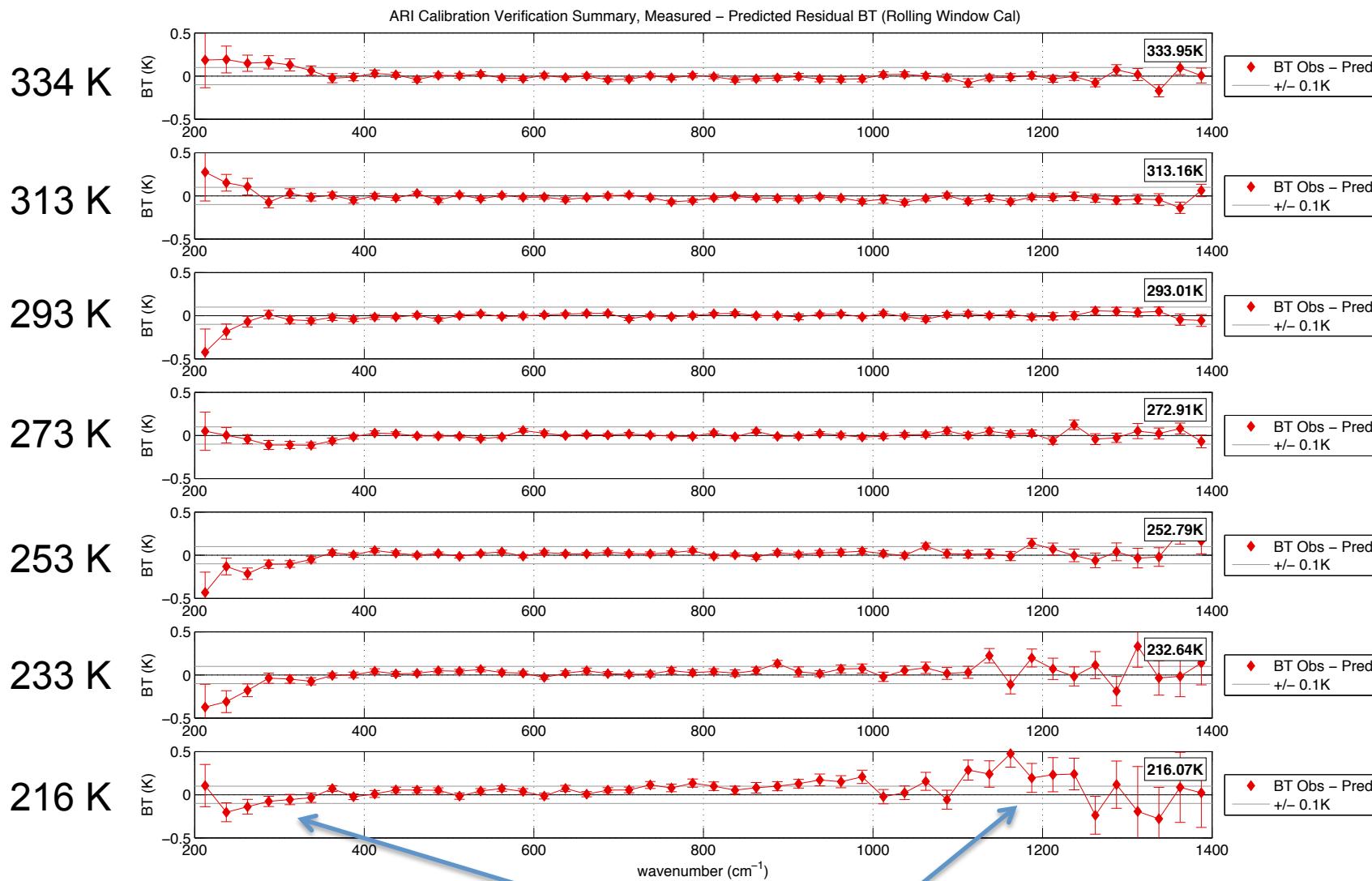
Difference from expected value is very close to zero + random noise

(noise is ~4 x noise for on-orbit noise spec due to shorter dwell times)

Brightness Temperature Residuals (DTGS)

(CFTS calibrated – OARS verification)

Error bars only include statistical error in measurement

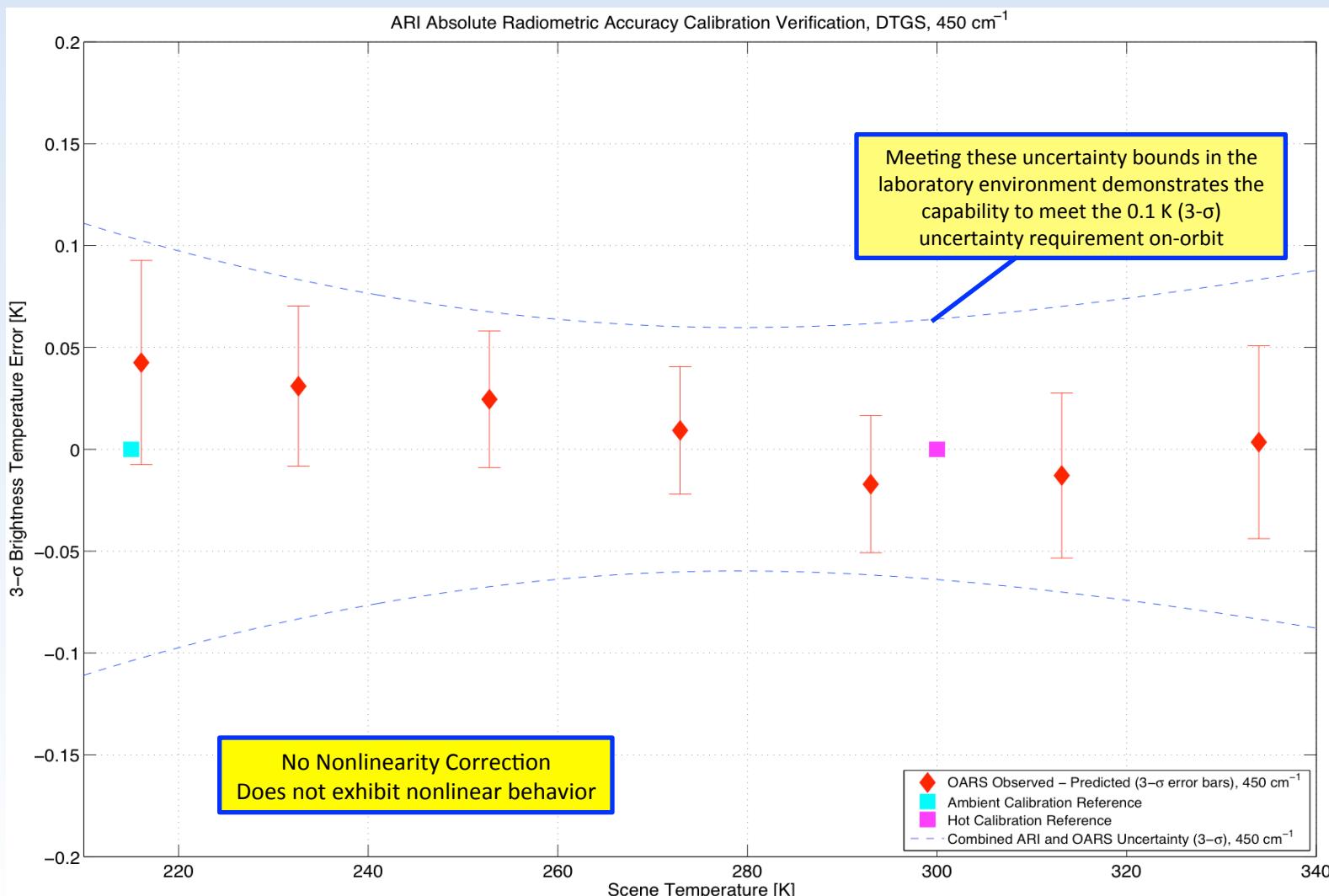


Spectral Averaging Bin Width is 25 cm^{-1}

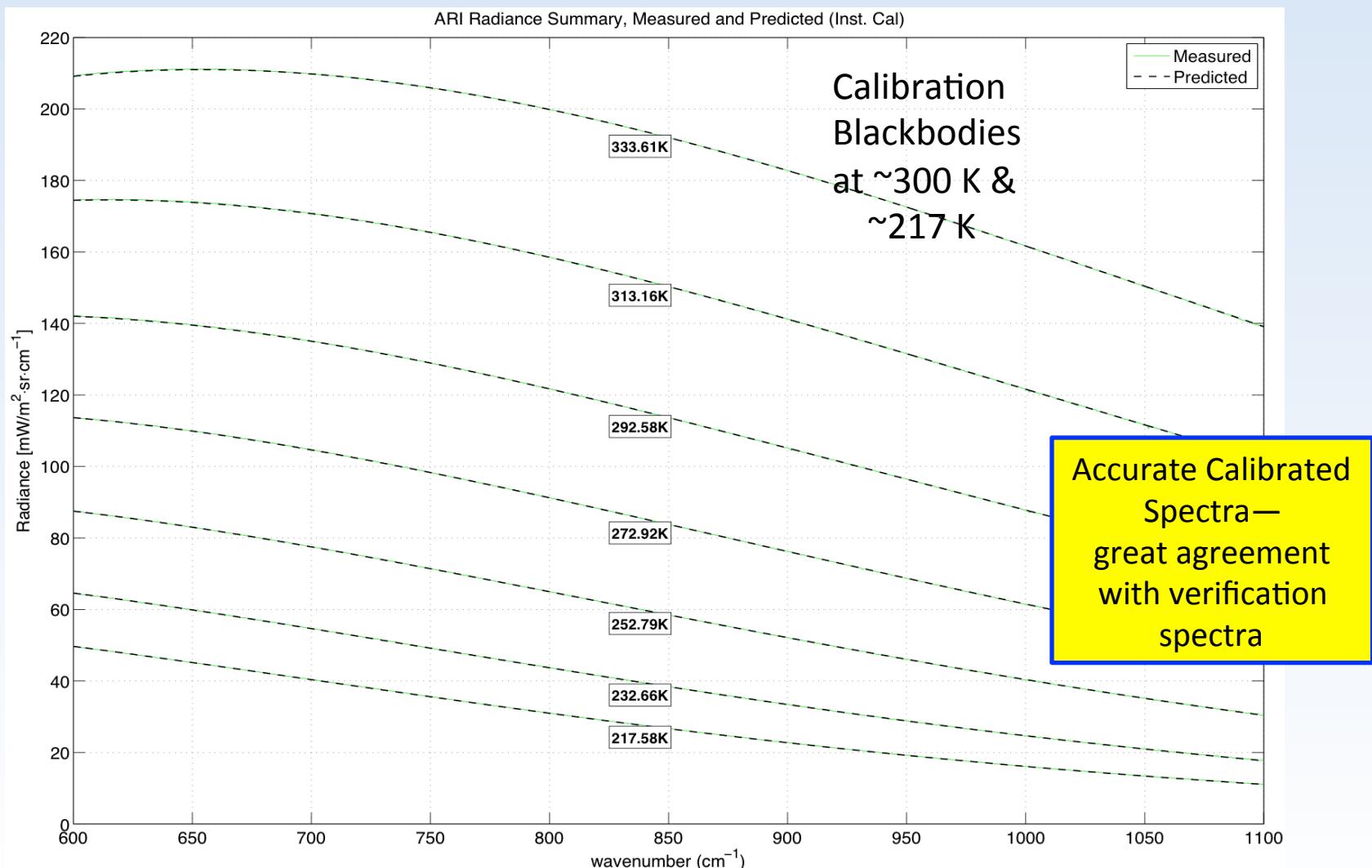
Bin averaged result subject to low SNR at band edges

Radiometric Calibration Verification

DTGS (400-500 cm⁻¹)



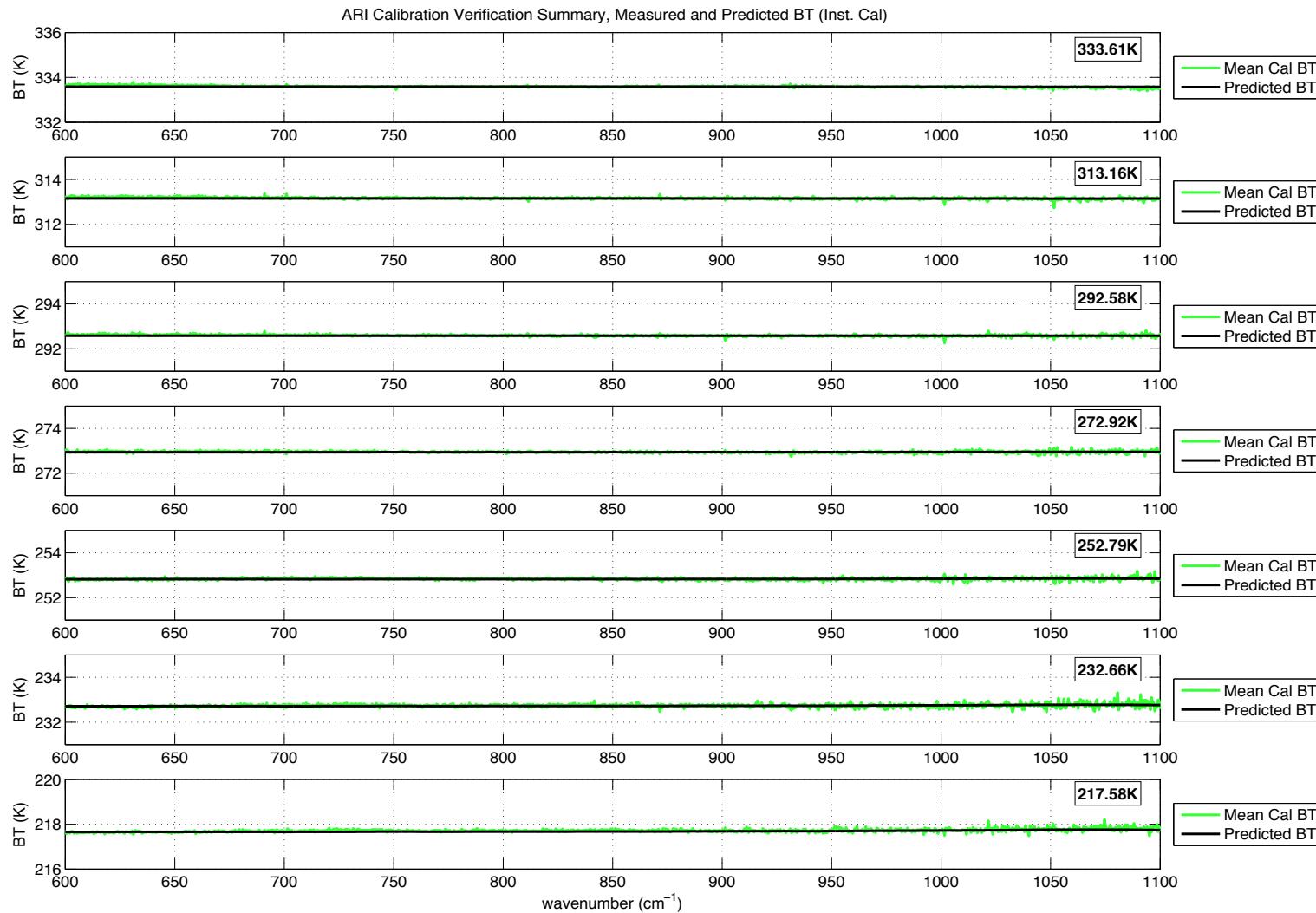
Mean Calibrated Radiance Spectra (MCT) Compared to OARS Radiance Spectra



Brightness Temperature (MCT with NLC)

(CFTS calibrated and OARS verification)

334 K

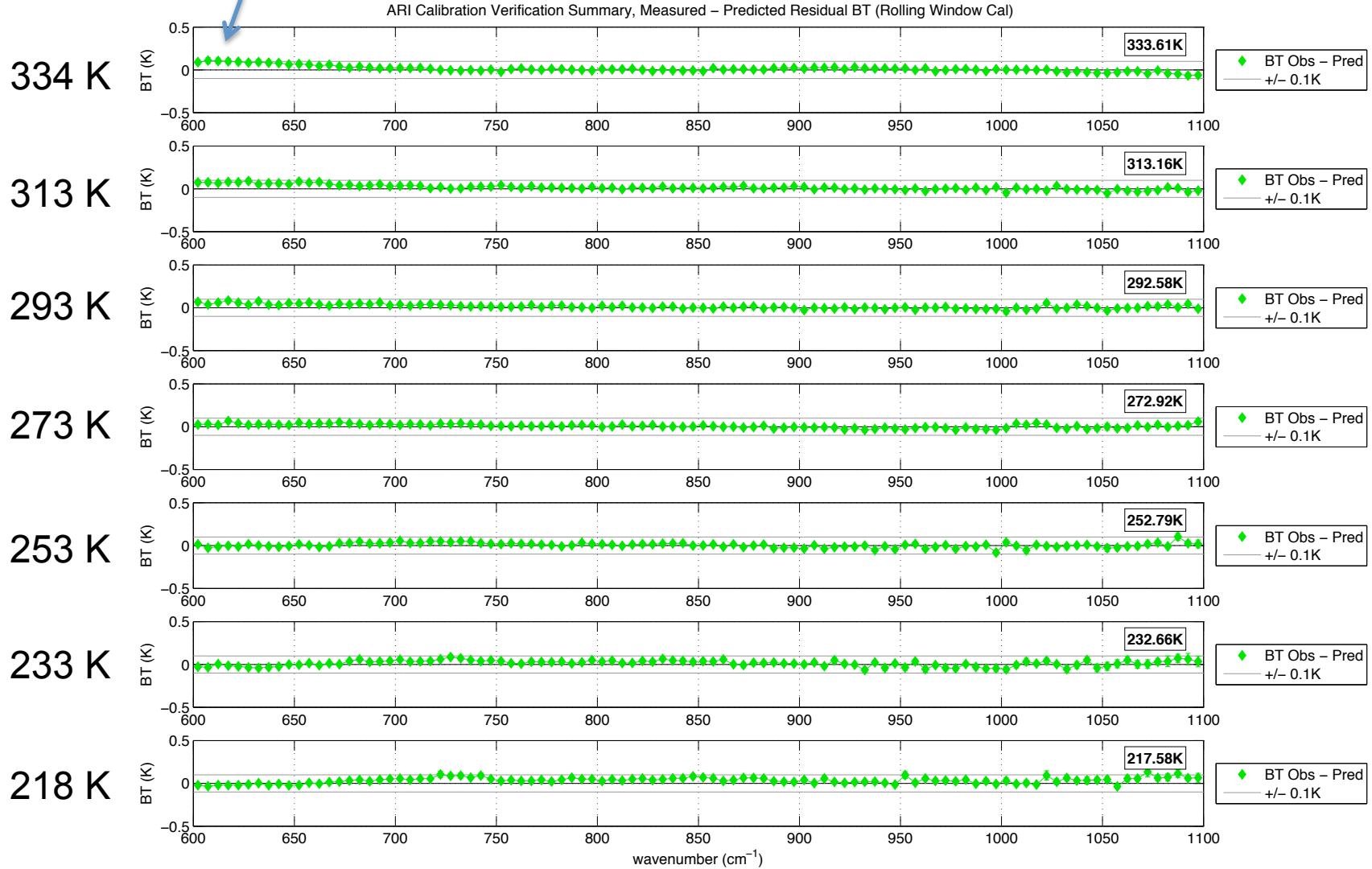


Brightness Temperature Residuals (MCT with NLC)

(CFTS calibrated - OARS verification)

MCT band Polarization induced error evident for hot target

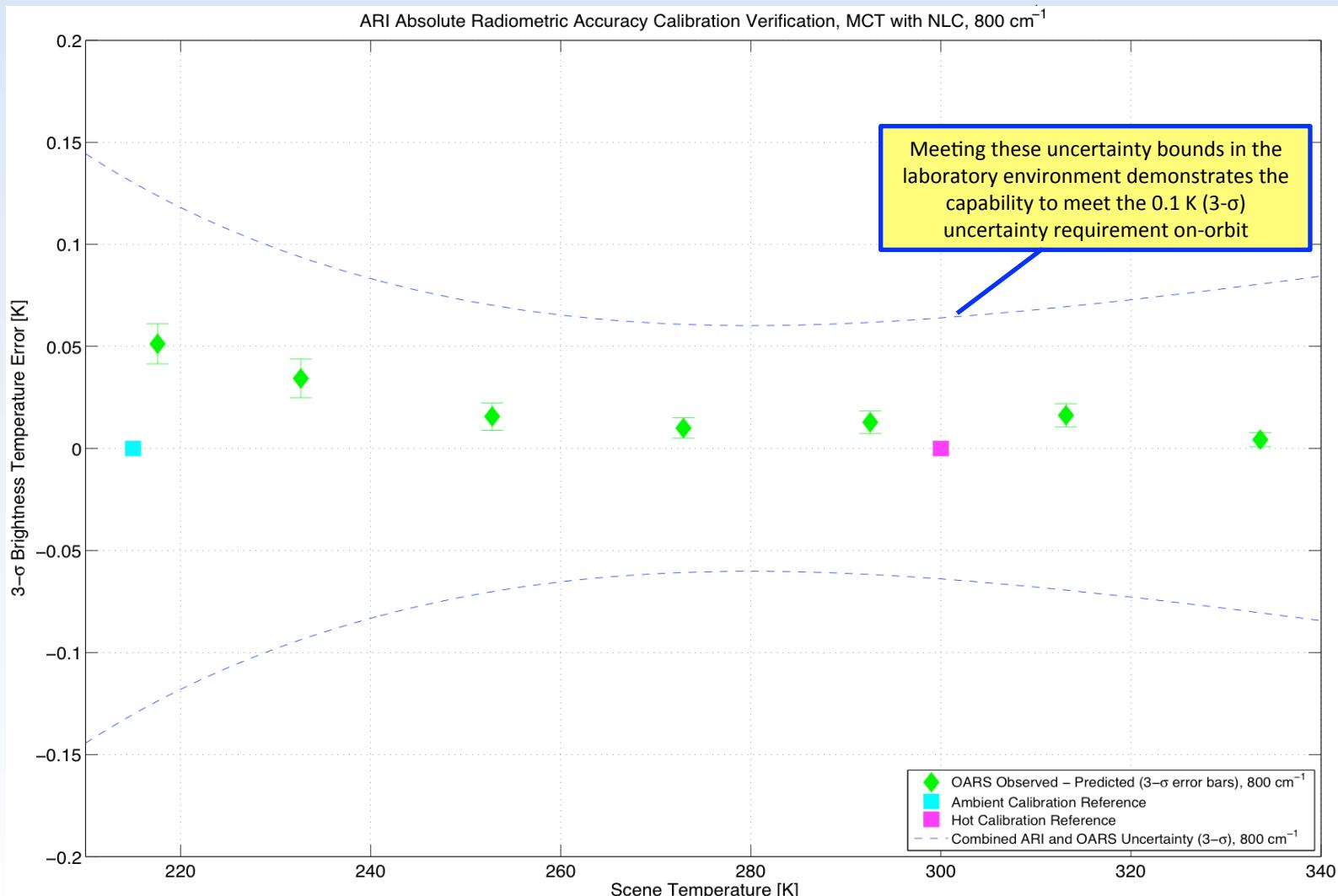
Error bars only include statistical error in measurement



Spectral Averaging Bin Width is 5 cm⁻¹

Radiometric Calibration Verification

MCT with NLC ($700\text{-}900\text{ cm}^{-1}$)

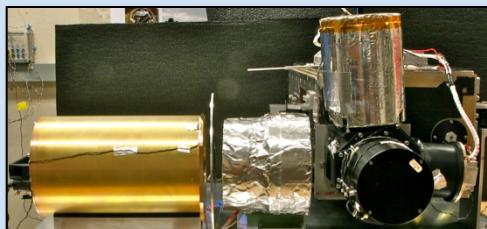


UW IIP Technology Development

Miniature Phase Change Cell (MPCC)



MPCC Component Integration,
Characterization and Accelerated Life Testing

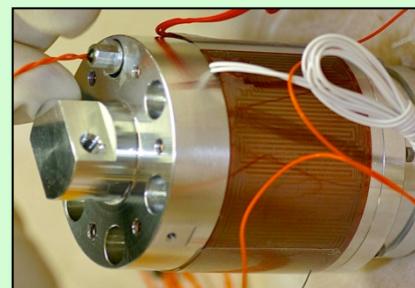


Heated Halo Generation-1 (Breadboard Halo,
AERI BB with Scanning HIS Aircraft FTIR)



Absolute Radiance Interferometer (ARI) Breadboard

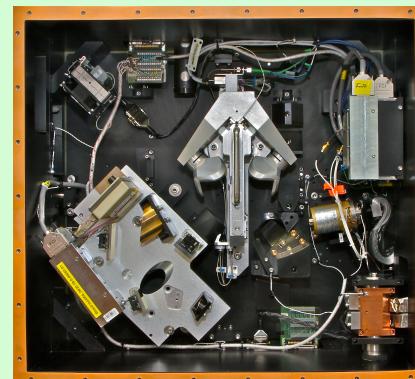
TRL 4



Integration of MPCC into Breadboard
Blackbody for Thermal Testing

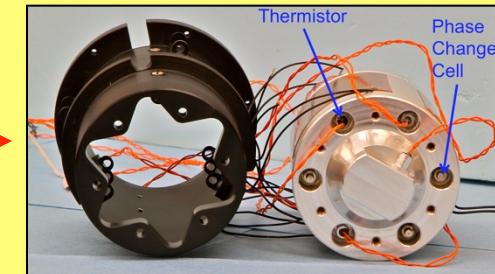


Heated Halo Generation-2 (Large Conical
Halo, AERI BB with ARI Breadboard FTIR)

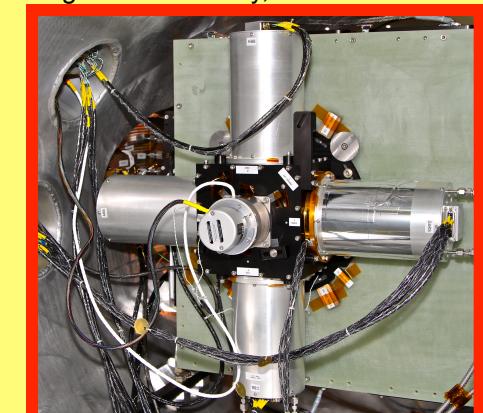


Absolute Radiance Interferometer Prototype

TRL 5



On-Orbit Absolute Radiance Standard:
New 30 mm Aperture BB with MPCC
integrated into cavity, and Heated Halo



ARI Prototype Tested in Vacuum

TRL 6

Ready for Flight Program

Radiometric Uncertainty (Predicted On-orbit, 3- σ)

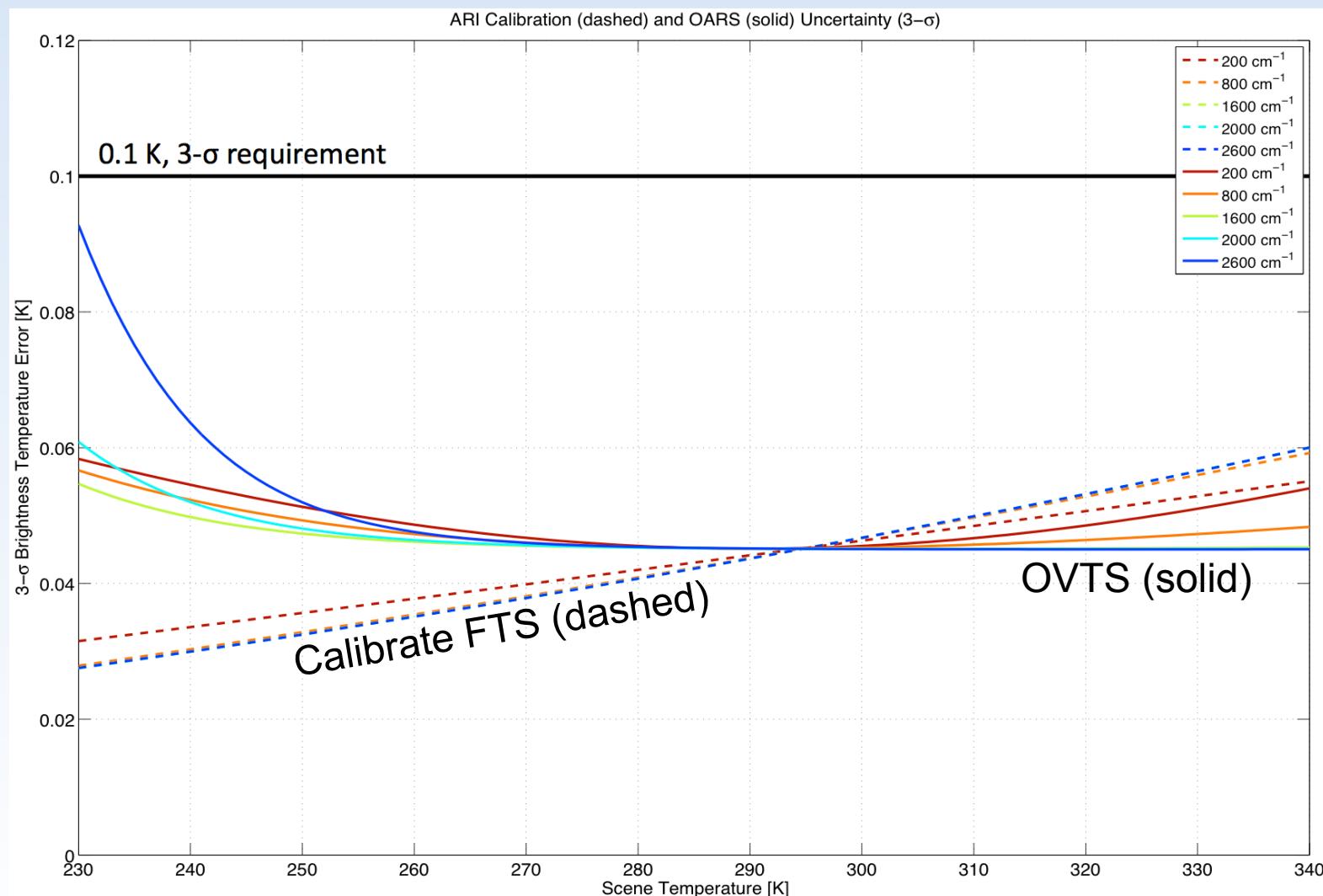
- On-orbit:
 - Space view for cold calibration reference
 - Onboard ambient calibration blackbody for “hot” calibration reference
 - These values satisfy the Zeus/CLARREO accuracy requirements

Temperatures			Associated Uncertainty (3- σ)	
Cold Cal Ref (Space Target)	T_c	4 K	$u(T_c)$	0 K
Hot Cal Ref (Internal Cal Target)	T_h	295 K	$u(T_h)$	0.045 K
Verification Target (OARS)	T_{OARS}	220 – 320 K	$u(T_{OARS})$	0.045 K
Reflected Radiance, Cold Cal Ref	$T_{R,C}$	290 K	$u(T_{R,C})$	0 K
Reflected Radiance, Hot Cal Ref	$T_{R,H}$	290 K	$u(T_{R,H})$	4 K
Reflected Radiance, Verification Target	$T_{R,OARS}$	290 K	$u(T_{R,OARS})$	4 K
Emissivities				
Cold Cal Ref (Space Target)	e_c	1	$u(e_c)$	0.0006
Hot Cal Ref (Internal Cal Target)	e_h	0.999	$u(e_h)$	0.0006
Verification Target (OARS)	e_{OARS}	0.999	$u(e_{OARS})$	0.0006*

* It has been assumed that the OARS emissivity and associated uncertainty is determined from prelaunch TVAC testing with a very high emissivity source

- $e_{OARS} = 0.9990 \pm 0.0006 \text{ (200 cm}^{-1}\text{)}$
- $e_{OARS} = 0.9990 \pm 0.0004 \text{ (800 cm}^{-1}\text{)}$
- $e_{OARS} = 0.9990 \pm 0.0002 \text{ (1400 cm}^{-1}\text{)}$
- $e_{OARS} = 0.9990 \pm 0.0001 \text{ (2000 cm}^{-1}\text{)}$
- $e_{OARS} = 0.9990 \pm 0.00075 \text{ (2600 cm}^{-1}\text{)}$

Radiometric Uncertainty (Predicted On-orbit, 3- σ)



* Uncertainty due to residual nonlinearity not shown

Conclusions

- Recent UW Vacuum Testing of CLARREO flight prototype (ARI) combined with prior UW/Harvard IIP technology developments and test results strongly support IR instrument readiness for a Climate Benchmark Mission
- We need to push for something to happen well before 2023!

Suggested Discussion Topic:

At AGU, in response to a question about the date for CLARREO on ISS being 2023 or later, Earth Science Division Director (Mike Freilich) said, “CLARREO Remains a Challenge”

What challenge remains? We have

- (1) Compelling science and societal benefit (Wielicki, et al., 2013),
- (2) Proven IR & RS technology (ESTO approved), and
- (3) An economical way to get started (namely ISS).

How can we get this across and move ahead??